Lighting the Standard Candle:
Nuclear Reactions in Type Ia Supernovae

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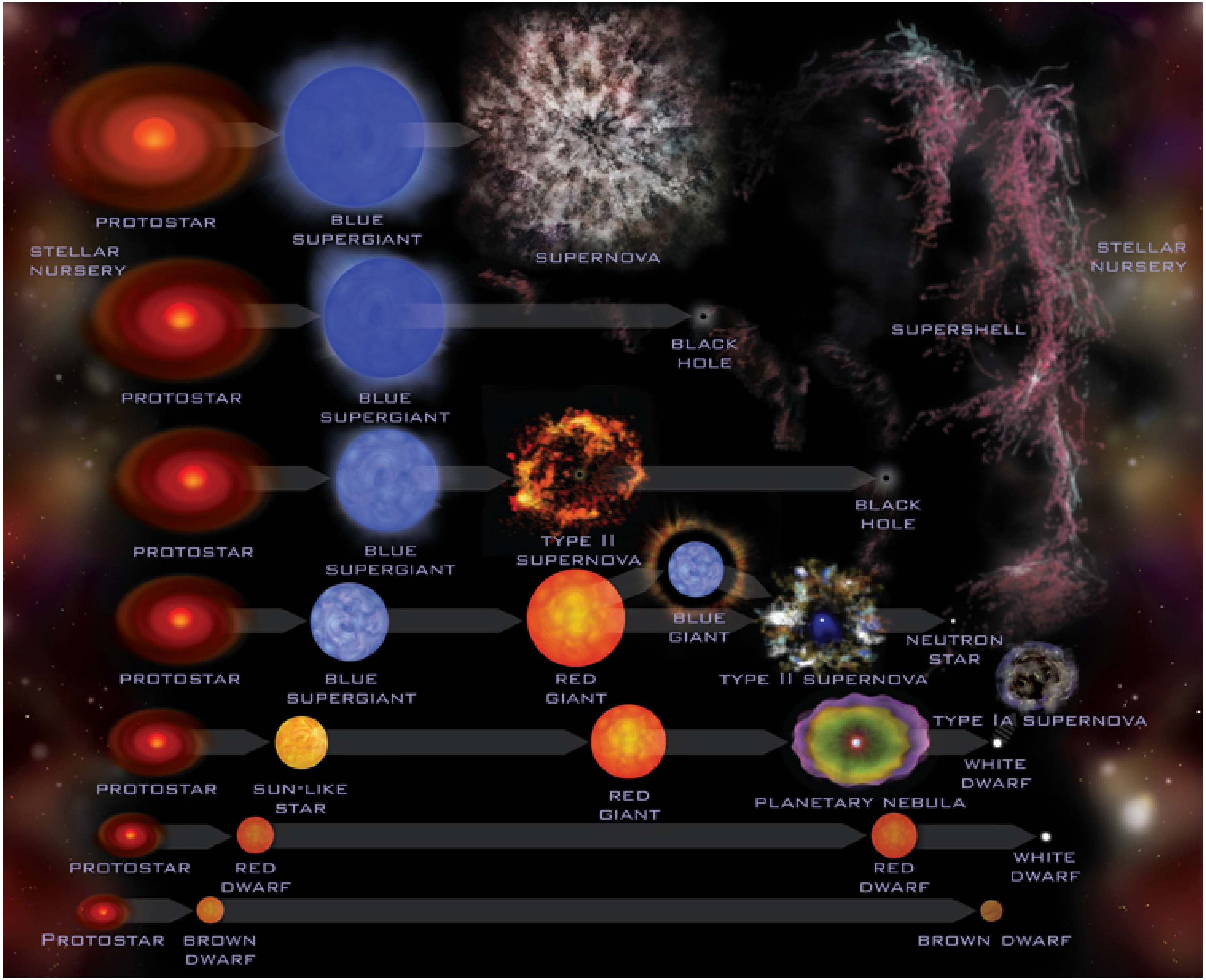
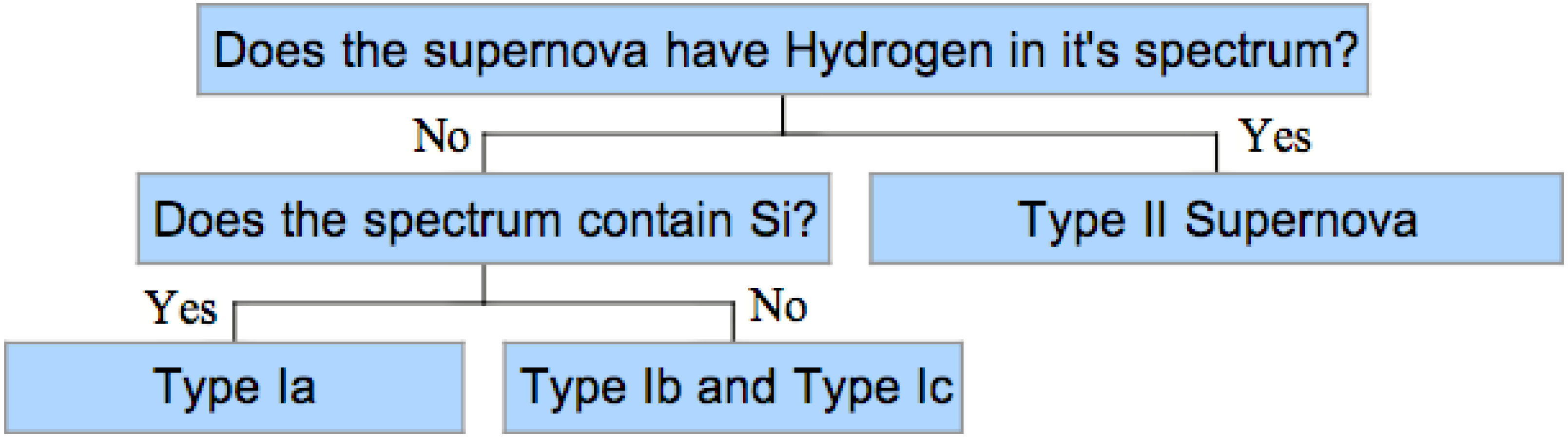
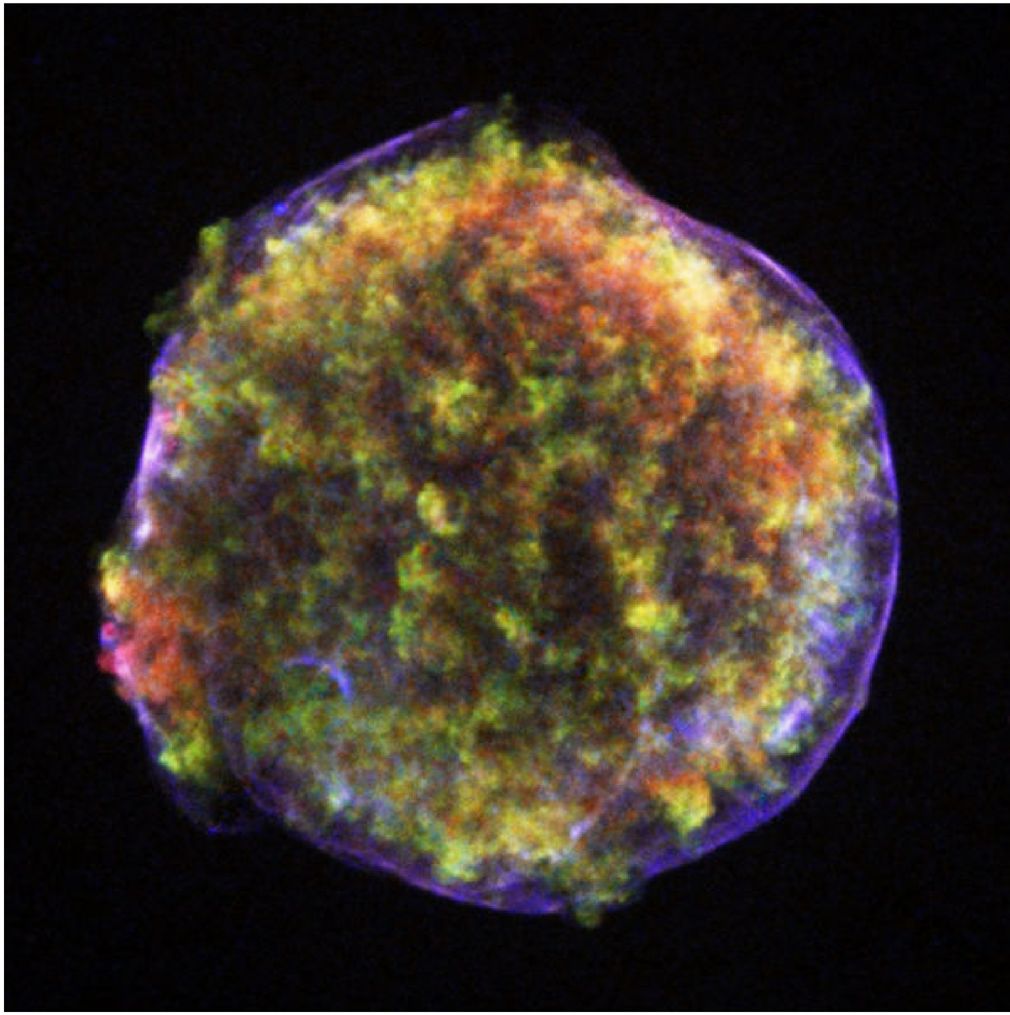

PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

The Different Kinds of Supernovae



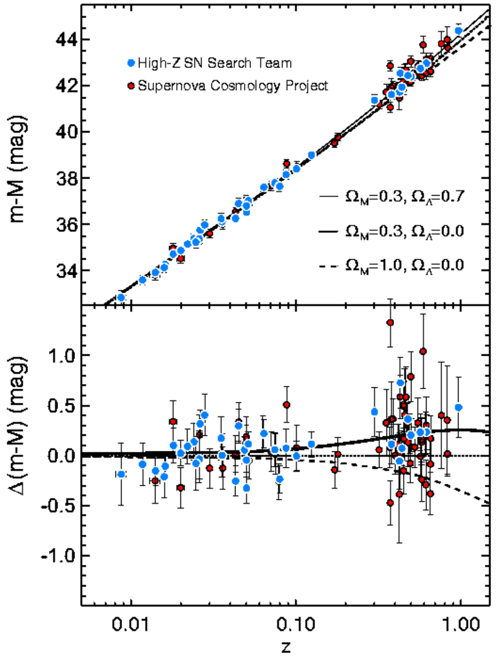
[The Hubble Key Project Team, and
The High-Z Supernova Search Team]



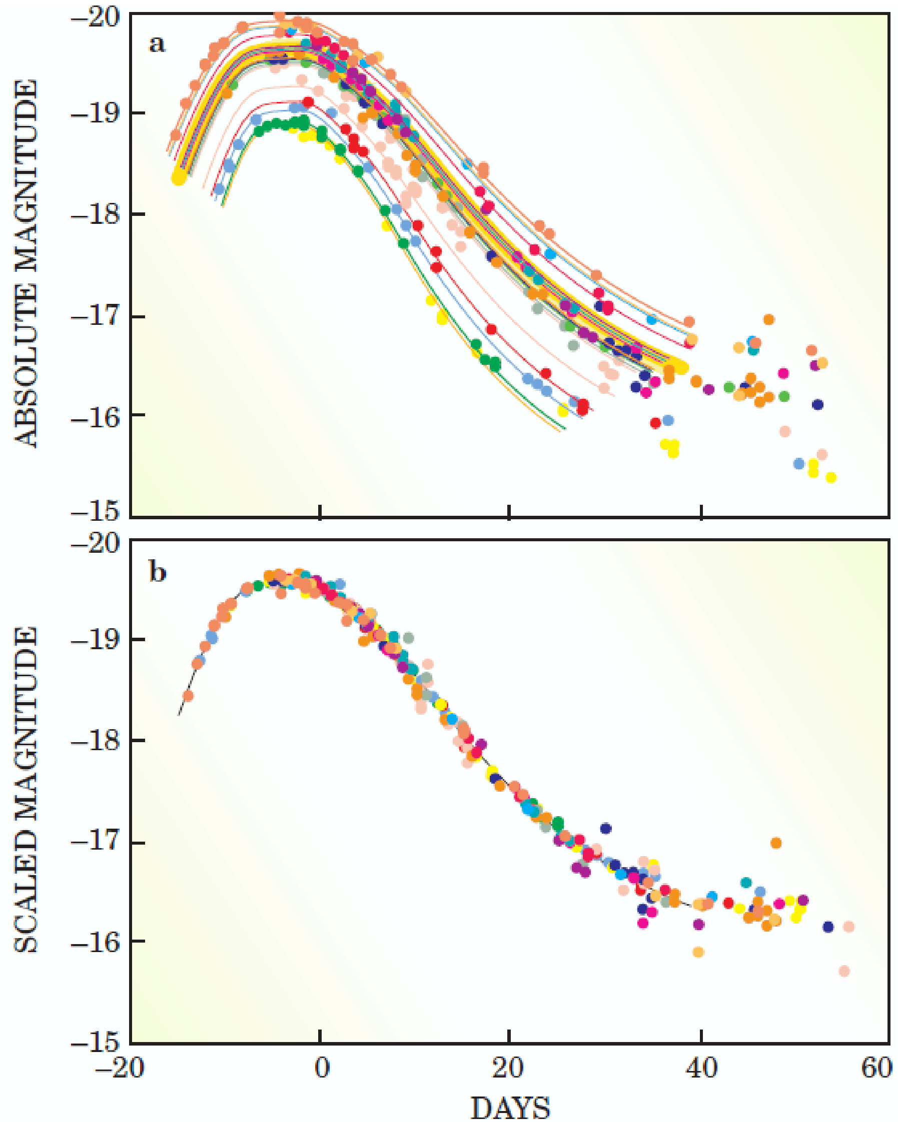
[NASA/CXC/Rutgers/J.Warren & J.Hughes et al.]

Type Ia supernova light curves have a property that allows them to be standardized

Use as standard candles is one of the principal methods of determining the equation of state of the universe.



[Riess et al. 1998]

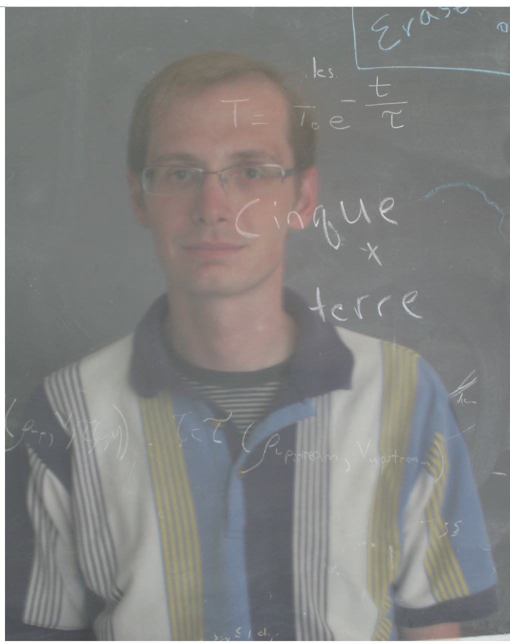


[Hamuy et al. 1995]

B
R
I
G
H
T

Luminosity:
Set by the abundance of ^{56}Ni

W
I
D
T
H



Opacity:

Set by the abundance of Fe group elements, the principal component of which is ^{56}Ni.

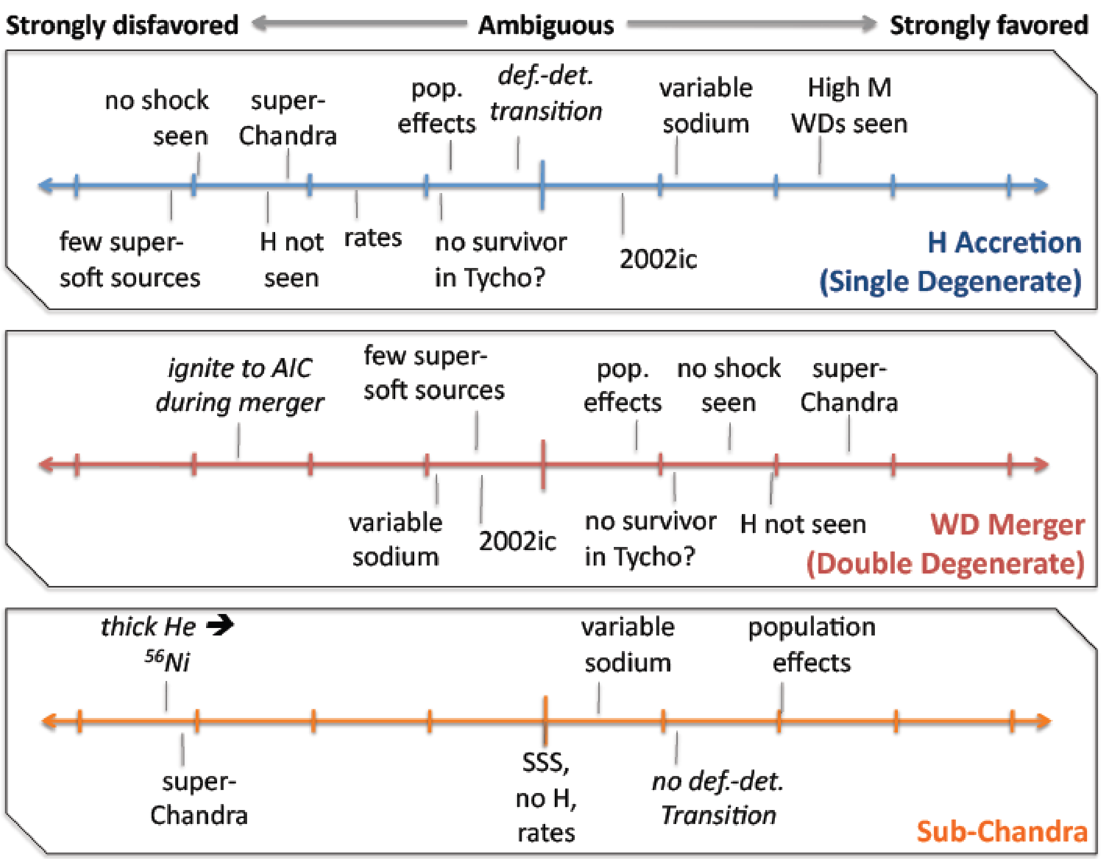
Kinetic Energy:

Set by how much fuel burned, is related to how much ^{56}Ni produced.

What do we know?

- No hydrogen.
- Range of ^{56}Ni mass between .3-1.0 M_{sun}
- Energy
  - 10^{51} ergs
  - 10^{51} TeV
  - 10^{28} Mtons
- Carbon lines seen at early times.

What do we really know?



[Howell 2010]

All we know about SNe Ia comes from observing the end results. We know very little about the progenitors.

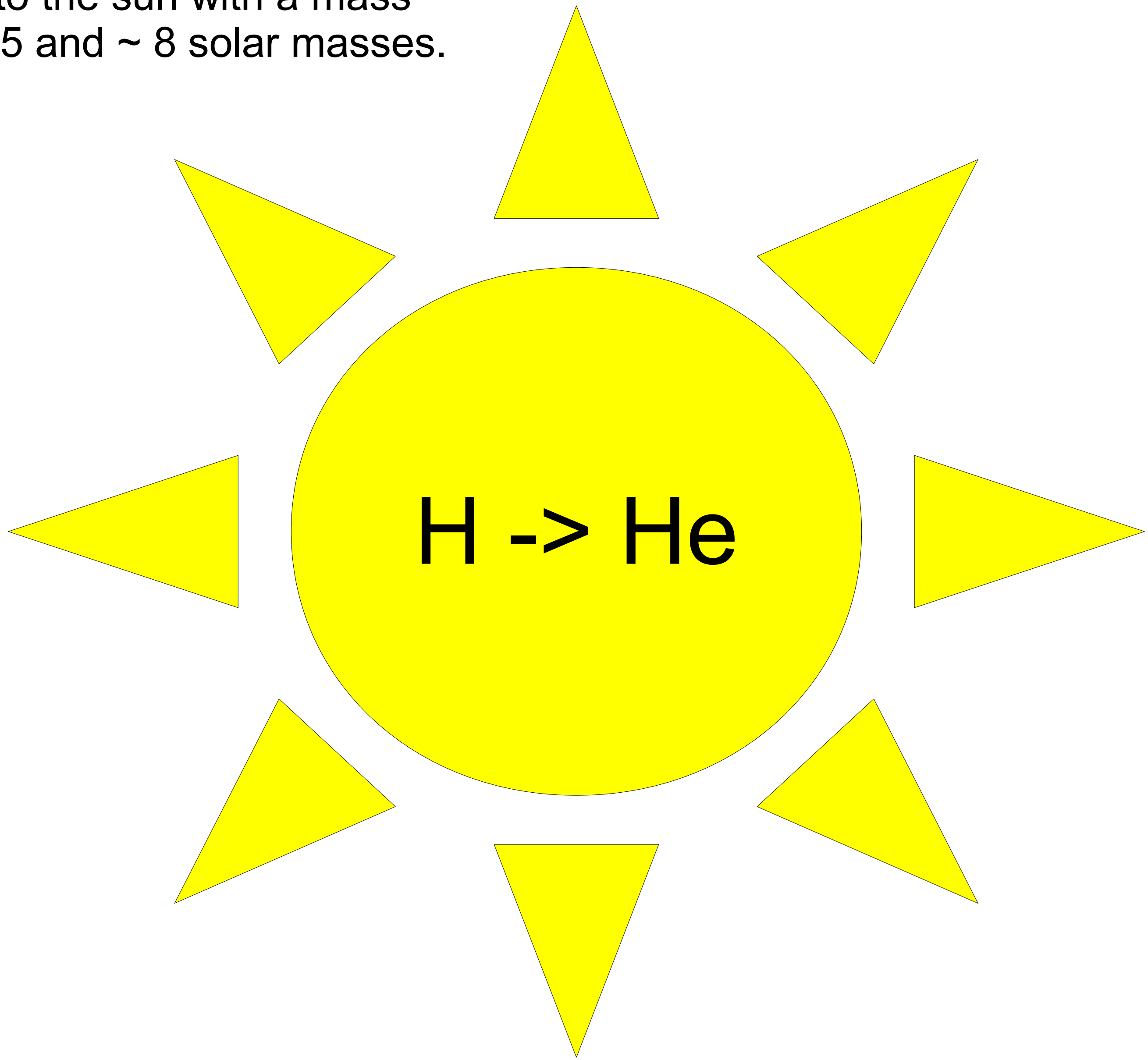
2010 Astronomy and Astrophysics Decadal Survey finds “What are the progenitors of Type Ia supernovae and how do the explode?” to be one of the top questions for the next decade.

H

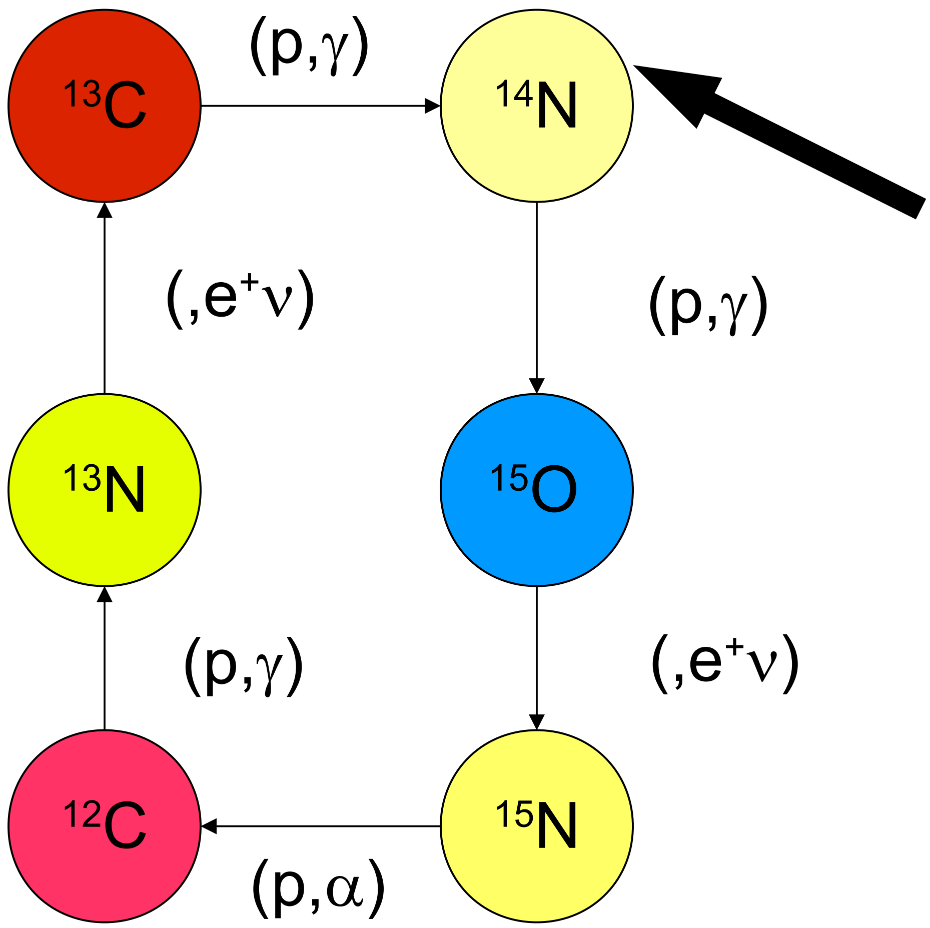
He

other stuff (C,O,Ne,Mg,Fe,U)

Star similar to the sun with a mass between 0.85 and ~ 8 solar masses.

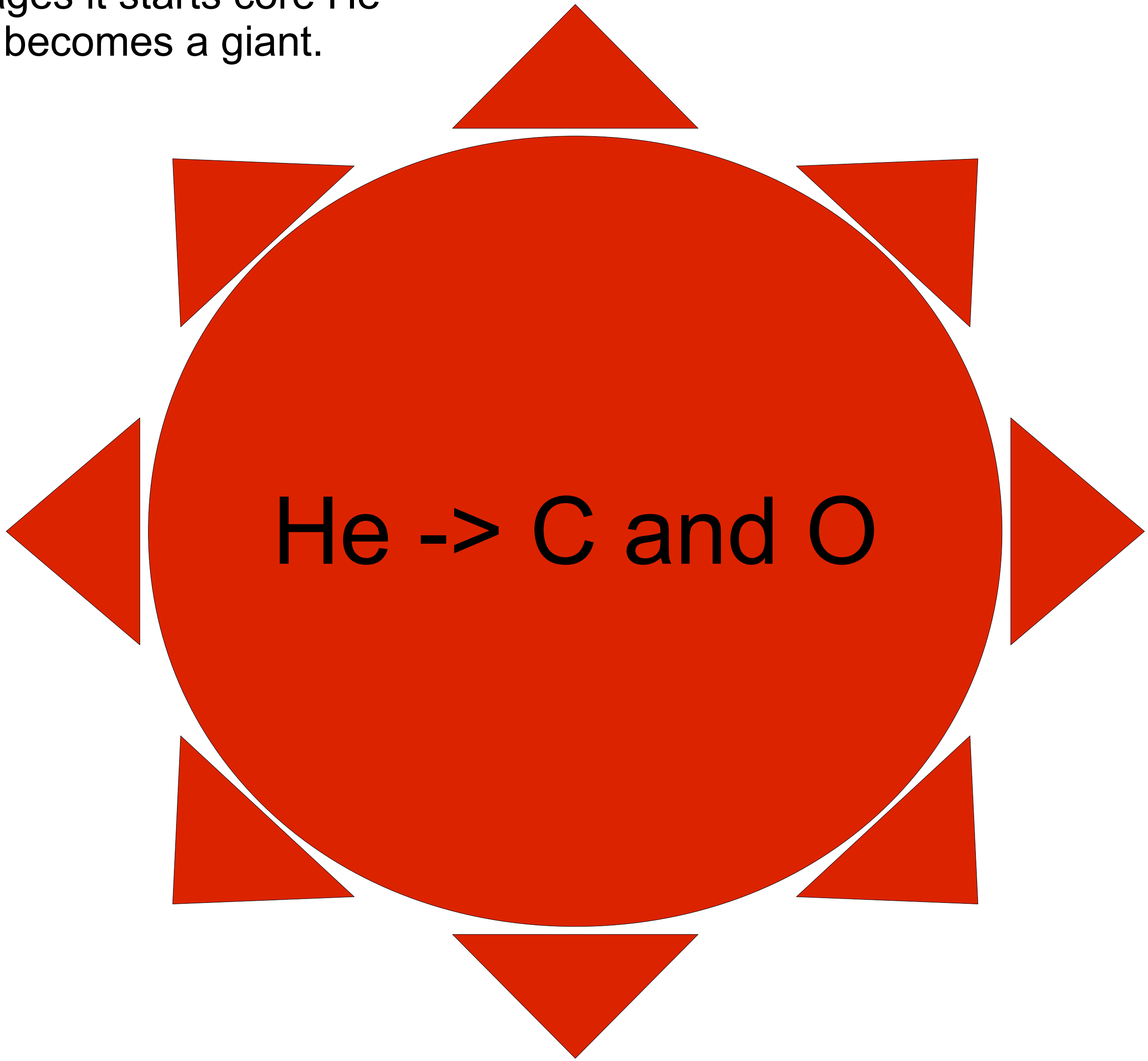


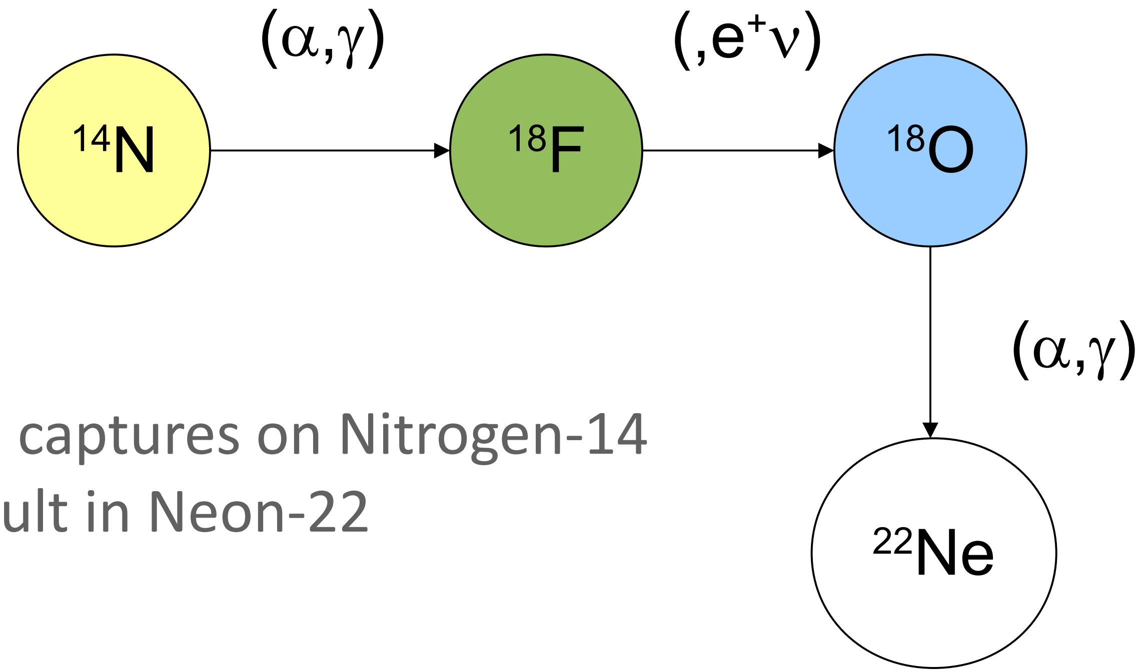
The CNO Cycle.



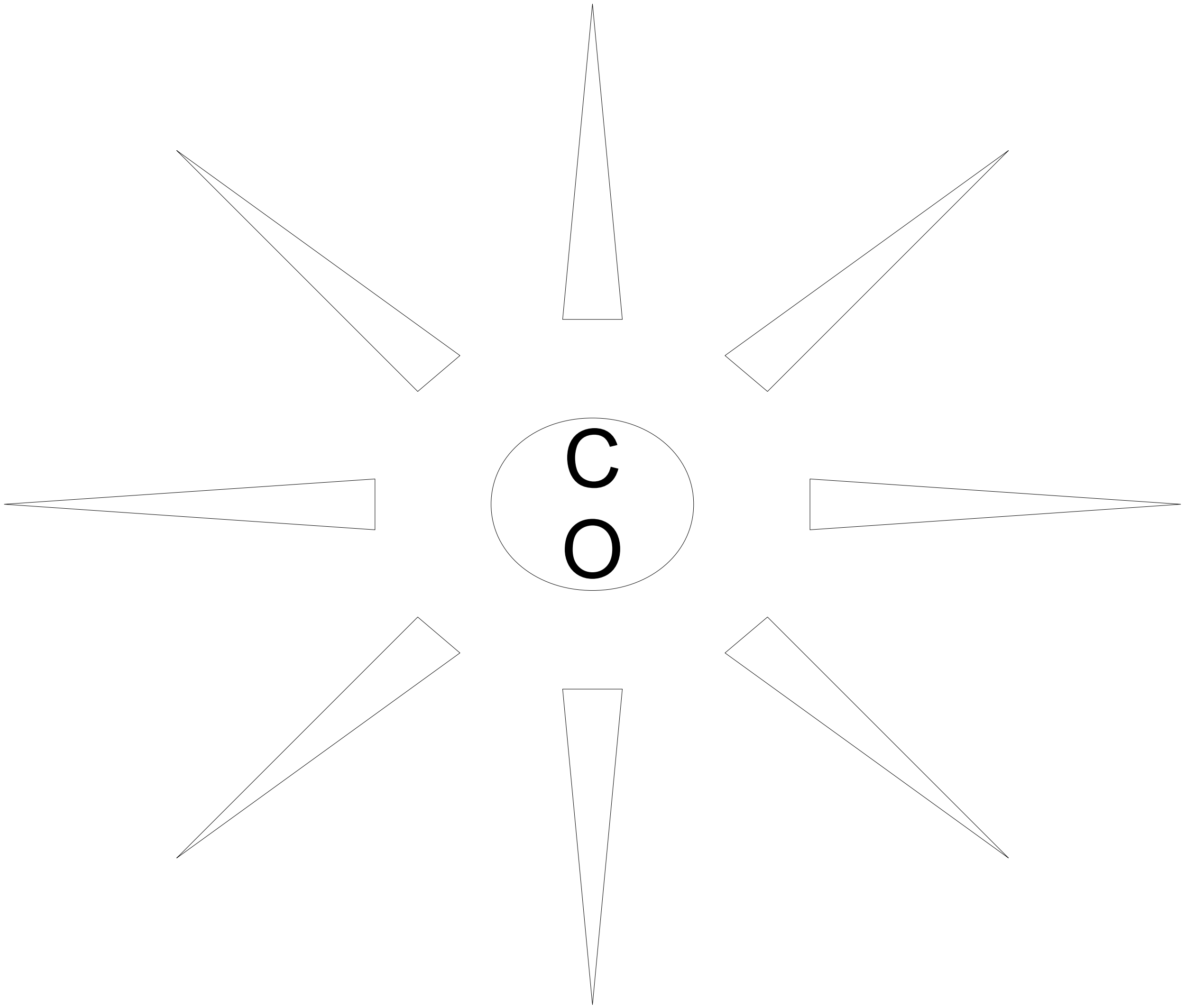
Nitrogen-14 is the waiting point in the CNO cycle.

As the star ages it starts core He burning and becomes a giant.





Alpha captures on Nitrogen-14 result in Neon-22

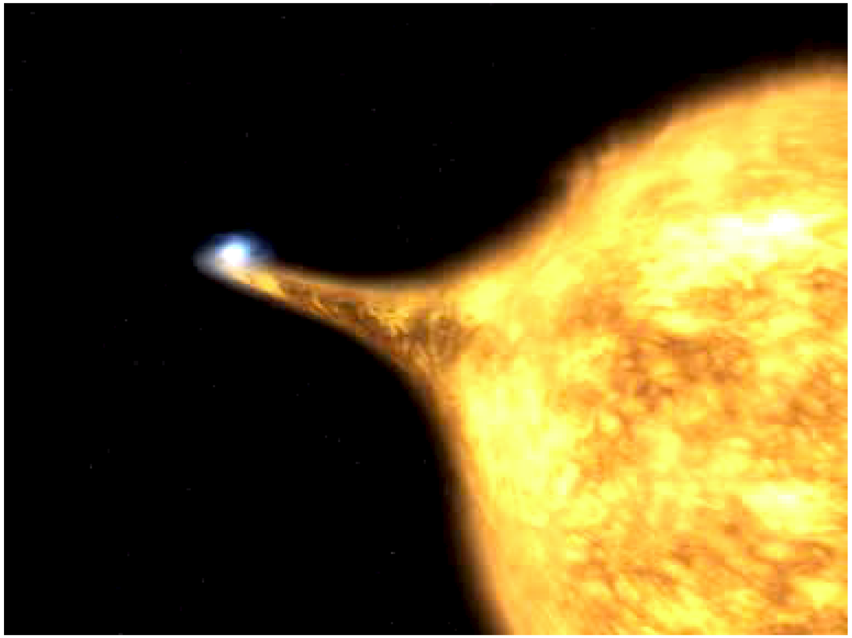


C/O White dwarf with mass less then 1 Msun

composition by mass for a star with solar metallicity:

^{12}C 30-60%
^{16}O 60-30%
^{22}Ne 2%

Accretion



[NASA]

All models are similar up to this point but start to diverge based on what is accreted.

Accretion from a companion star adds mass to the white dwarf.

Helium shell flashes may enrich the white dwarf in s-process elements. [Iben 1981]

Thermonuclear incineration of a C/O white dwarf near the Chandrasekhar limit (1.4 Solar Masses). [see Hillebrandt & Niemeyer 2000]

Most of the material is iron peak with silicon group elements.

About 0.6 Msun of matierial is ^{56}Ni.

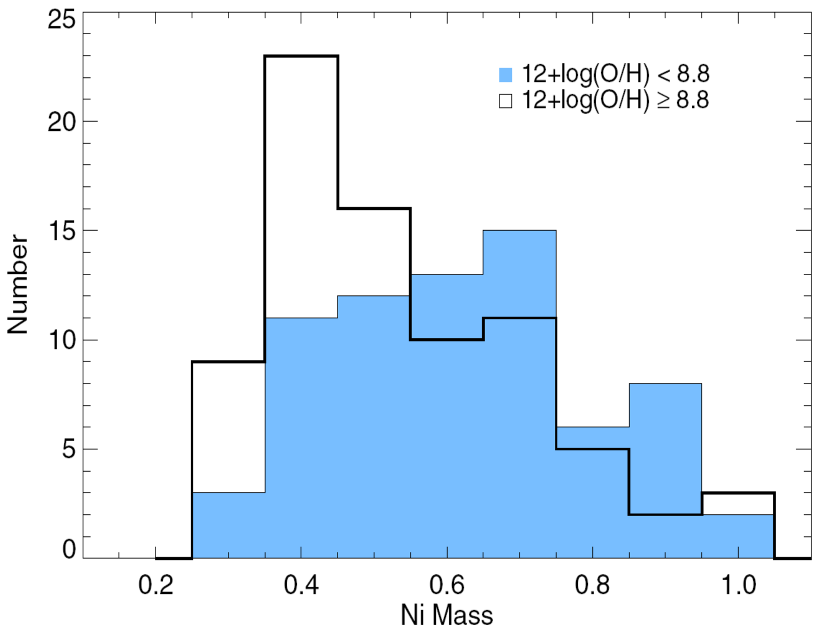
May produce p-process [Kusakabe][Travaglio].

Why Metallicity

Surveys have shown that SNe Ia have some knowledge of the galaxy that they are in.

Composition is determined from host galaxy photometry.

Ni mass is determined from Luminosity



[Howell et al. 2009]

For Example

$$2\,^{12}C + 2\,^{16}O = {}^{56}Ni$$

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$$2\,{}^{12}C + 3\,{}^{16}O + 2\,{}^{22}Ne = 2\,{}^{56}Ni + 4\mathrm{n}$$

For Example

$$2\,^{12}C + 2\,^{16}O = {}^{56}Ni$$

Excess neutrons will capture onto the heavy nuclei.

$$2\,^{12}C + 3\,^{16}O + 2\,^{22}Ne = 2\,^{56}Ni + 4\mathrm{n}$$

$$\cdots = 2\,^{58}Ni$$

The nickel formed is not radioactive and therefore will not contribute to the brightness of the supernovae.

The formal approach

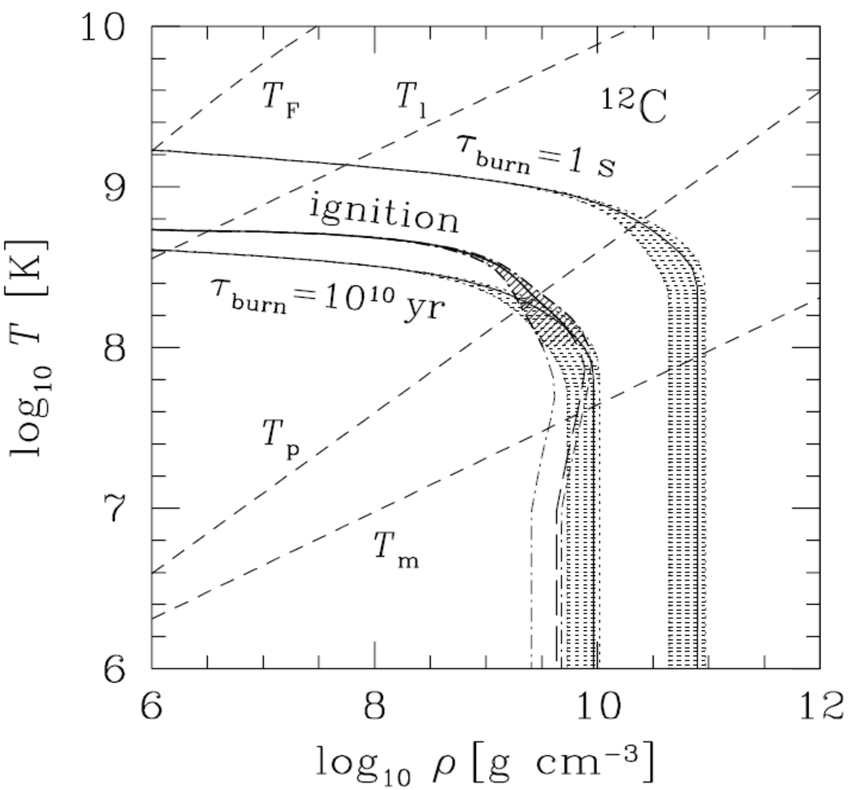
Lets pretend that ^{56}Ni and ^{58}Ni are the only species in the burned fuel. The equations for mass and charge conservation imply that

$$M(^{56}Ni) \approx 0.6(1 - 0.057\, Z/Z_{sun})$$

This results in a scatter of about 0.1 M in peak brightness, assuming no other metallicity dependent effects.

[Timmes, Brown, Truran 2003]

- As matter is accreted the centre of the white dwarf increases in temperature and density.
- A period of convective burning starts.
- When the star can no longer adjust to the heat being released a flame is launched.
- The flame is hot enough to burn material to nuclear statistical equilibrium.



[Gasques et al. 2007]

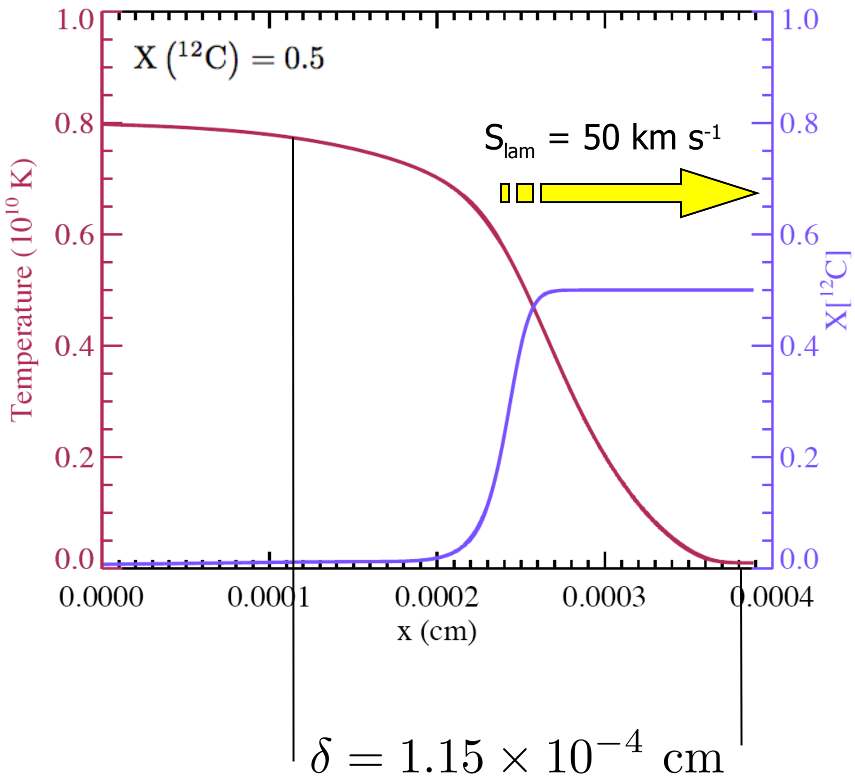
Deflagration

$$S_{lam}\left[\frac{dE}{dx}+P\frac{d(1/\rho)}{dx}\right]=\frac{1}{\rho}\frac{d}{dx}\left(K\frac{dT}{dx}\right)+\varepsilon$$

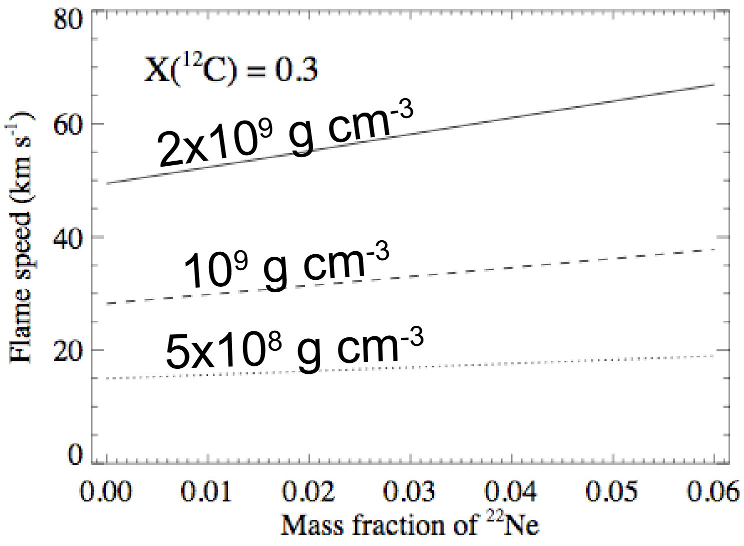
$$\varepsilon = N_A\sum_i B_i\frac{dY_i}{dt}$$

PdV work   heat flux

Nuclear flame is just like any other flame except instead of being powered chemical reactions, nuclear reactions provide the energy source.



Flame Speedup



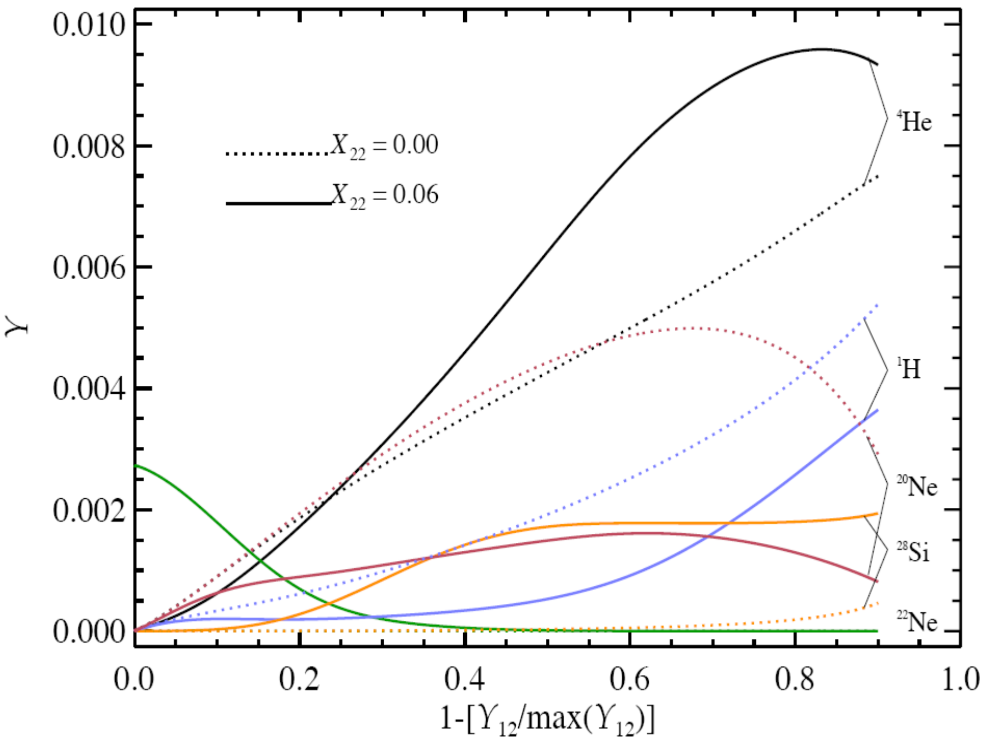
[Chamulak et al. 2007]

Increasing the ^{22}Ne abundance increases the flame speed linearly.

A 3 times solar abundance of ^{22}Ne increases the flame speed by 30%!

The extra neutrons are able to allow for more reactions to take place in the flame front resulting in greater energy release

Why the Speed up?



[Chamulak et al. 2007]

Many reactions happen in the flame front.

(α,n) provides a source of neutrons.

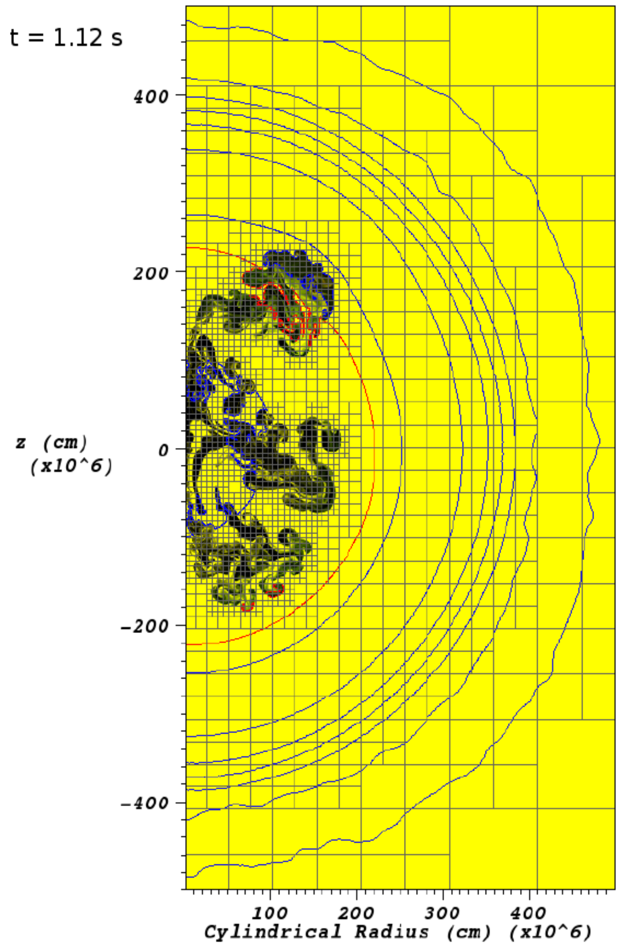
The addition of neutrons opens up reaction channels that consume protons to form He releasing additional energy in the flame front.

Flash

- Developed by the ASC Flash center at the University of Chicago
- Eulerian compressible hydrodynamics code
- Capable of doing hydrodynamics in 1-D, 2-D or even 3-D
- Free to download off the web.

Flame Evolution

- Shortly after the flame starts Rayleigh-Taylor instabilities take over. [Zingale et al.]
- The turbulent eddies starts out large become ever smaller
- The flame is carried around by the turbulence increasing its speed
- Fuel is mixed with ash
- Townsley et al. 2009 has shown flame speed does not affect ^{56}Ni production assuming there are no change in the density at which the detonation happens at.



[Townsley et al. 2009]

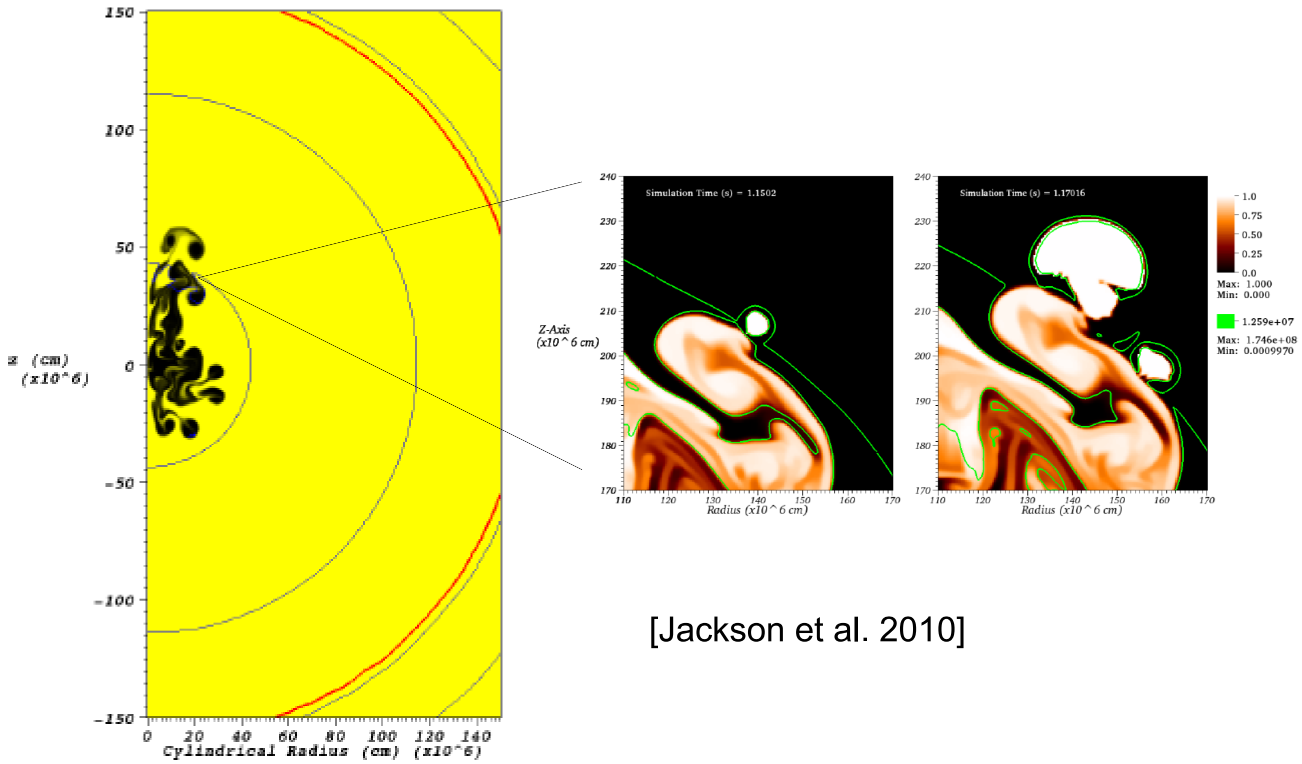
Detonation

- It is necessary to invoke a detonation in models of Type Ia supernovae.
- There are different prescriptions for how to do this.
- Deflagration to detonation transition (DDT)
  - Happens in every day life
  - Dependent on boundary conditions
  - Turbulent eddies interact with the flame

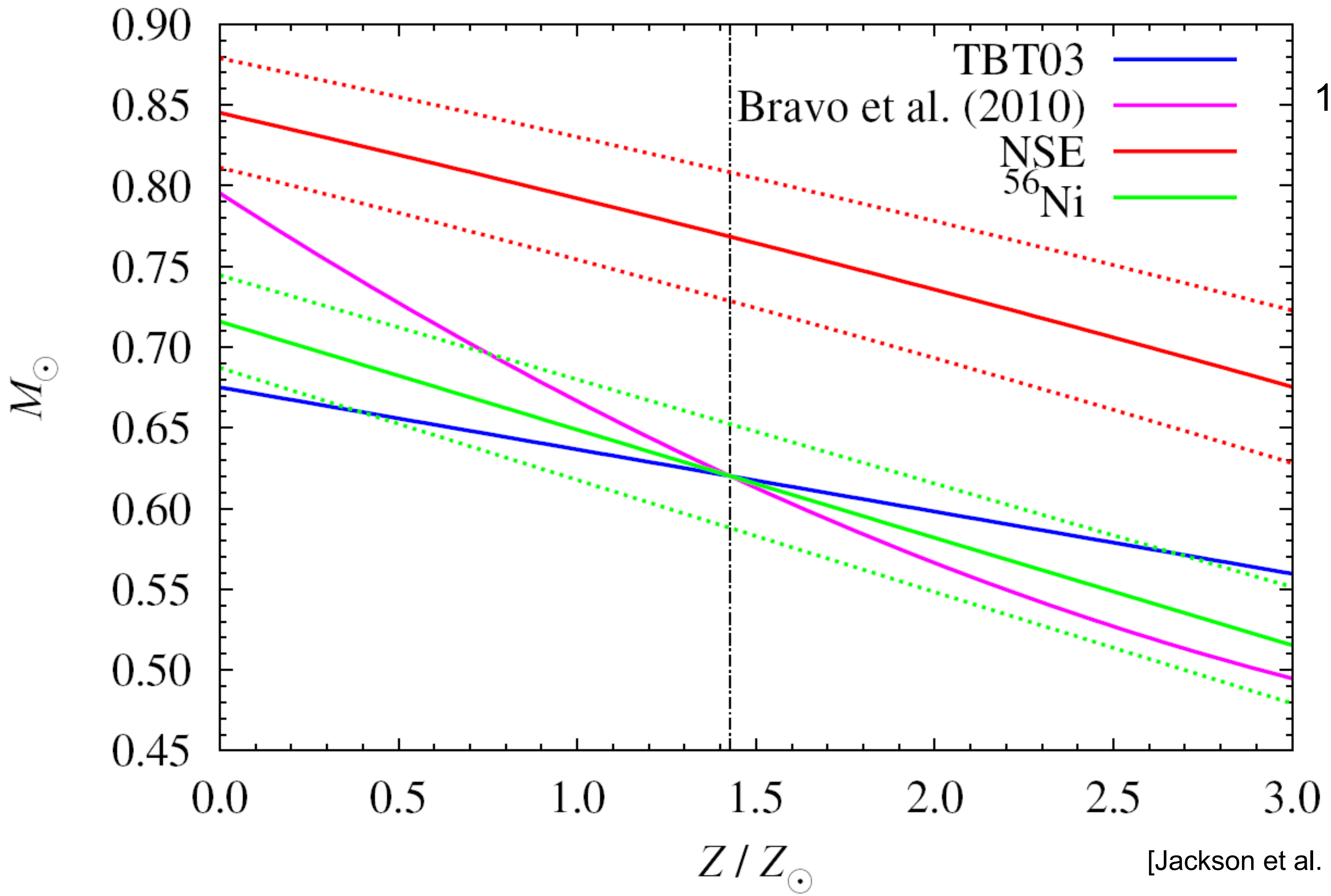
The Model Considered

Deflagration to detonation transition (DDT)

Transition is dependent on flame speed and width



[Jackson et al. 2010]



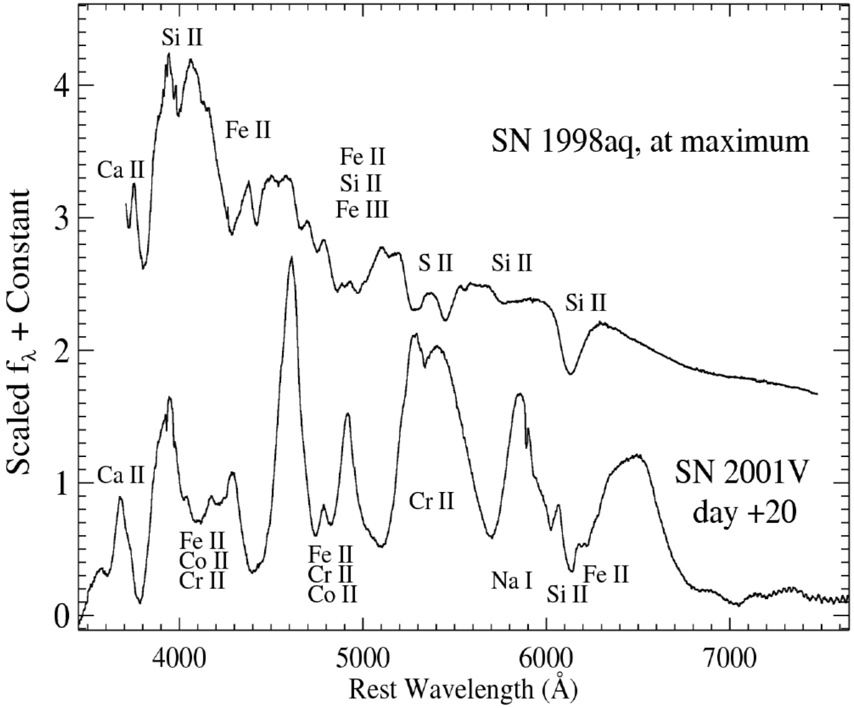
1-D model

[Jackson et al. 2010]

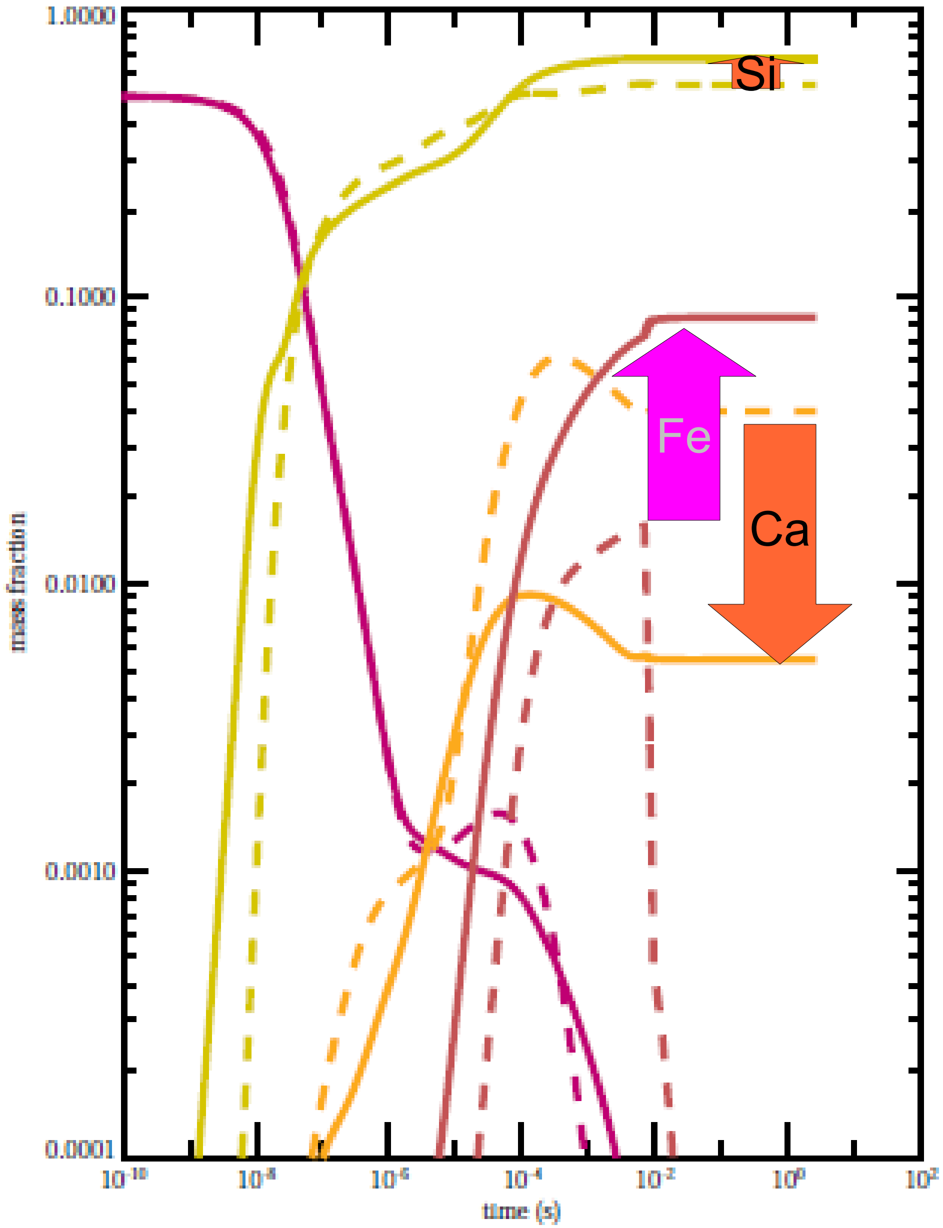
Now what?

Composition is determined from host galaxy photometry.

Is there a way to determine the actual metallicity of the progenitor?



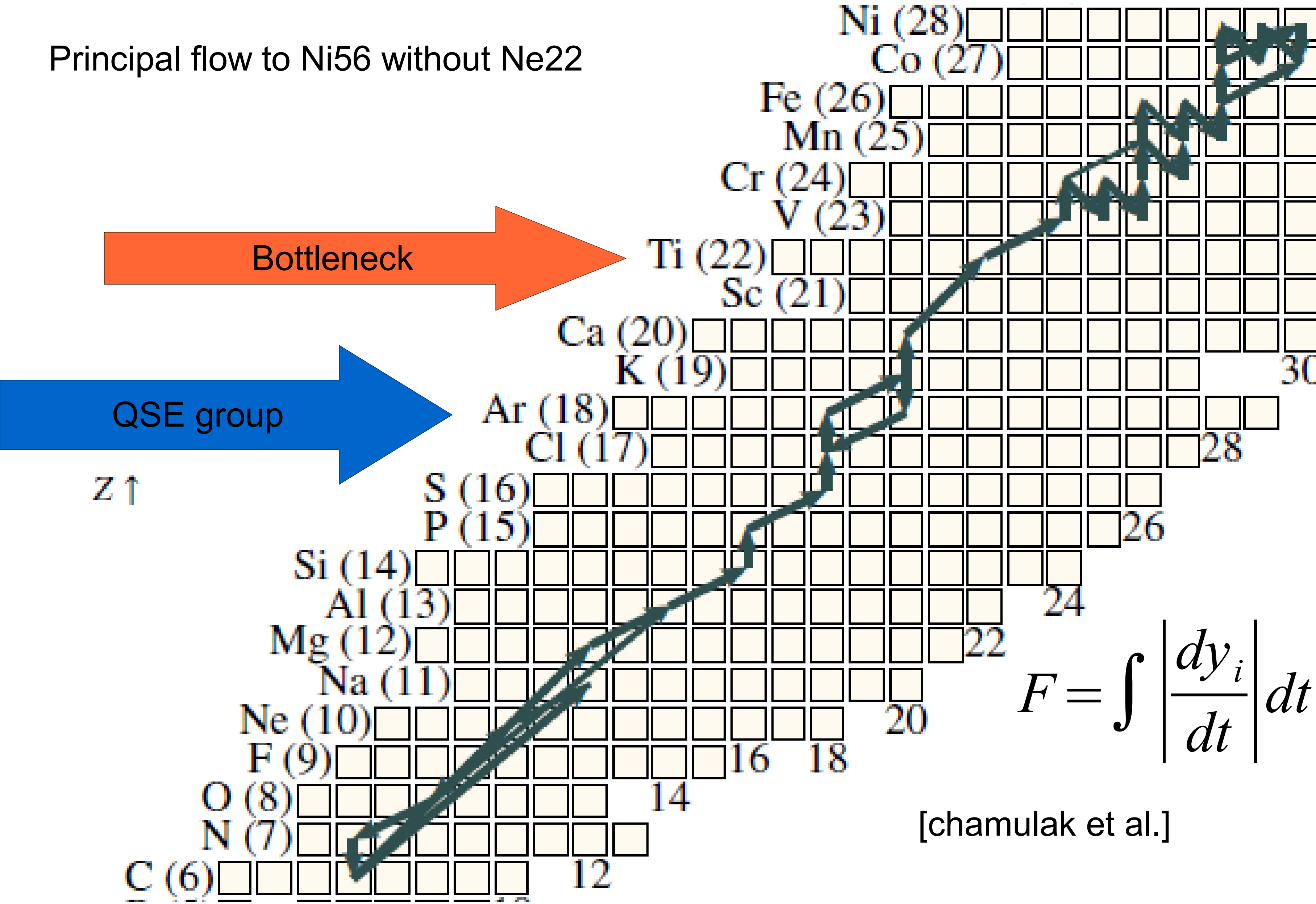
[Matheson et al. 2008]



Going from no Ne22 to 3x solar metallicity of Ne22 causes the production of Si, and Fe to increase, and the production of S, Ar, Ca all to decrease.

[chamulak et al.]

Principal flow to Ni56 without Ne22

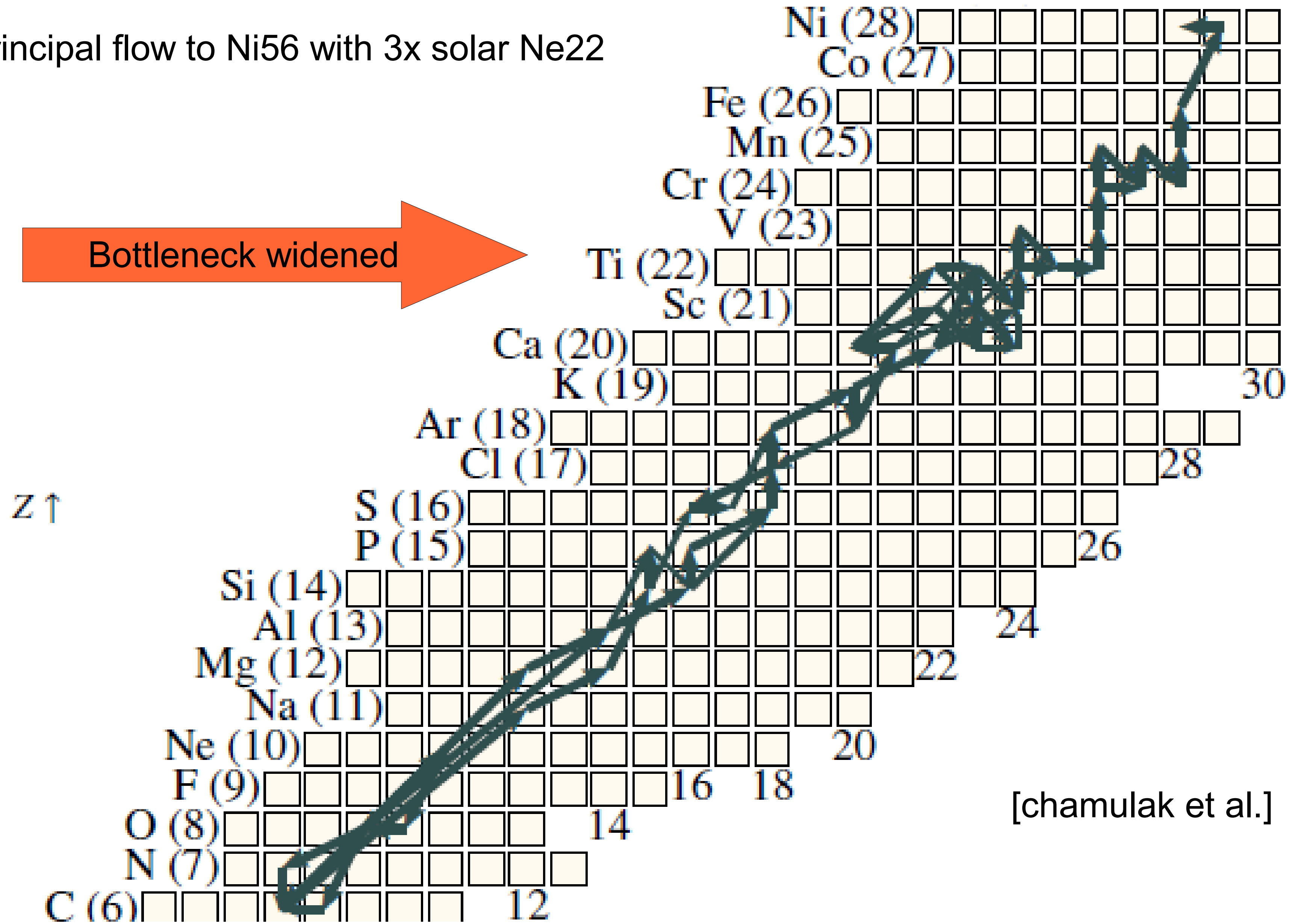


$$F = \int \left| \frac{dy_i}{dt} \right| dt$$

[chamulak et al.]

Principal flow to Ni56 with 3x solar Ne22

Bottleneck widened

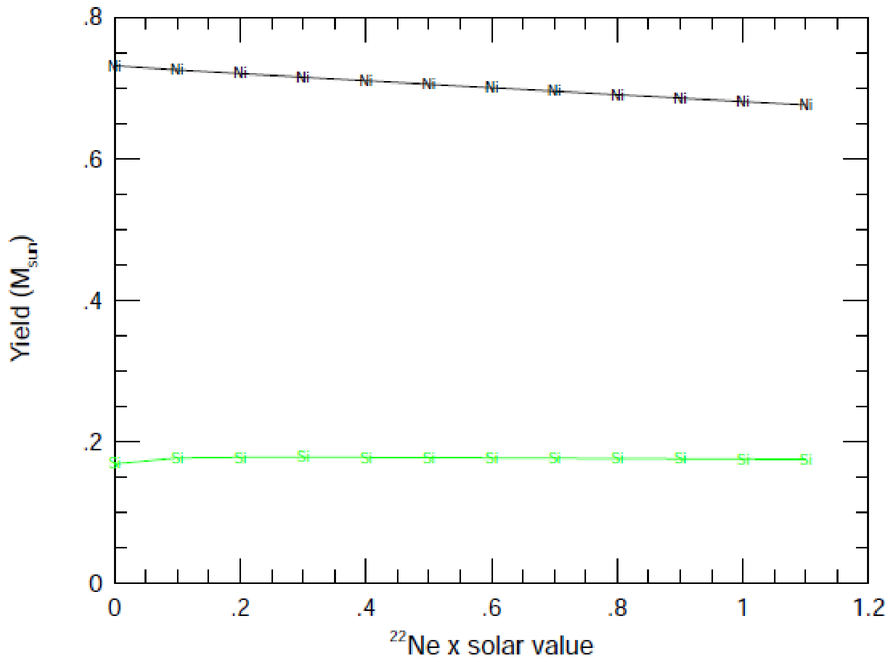


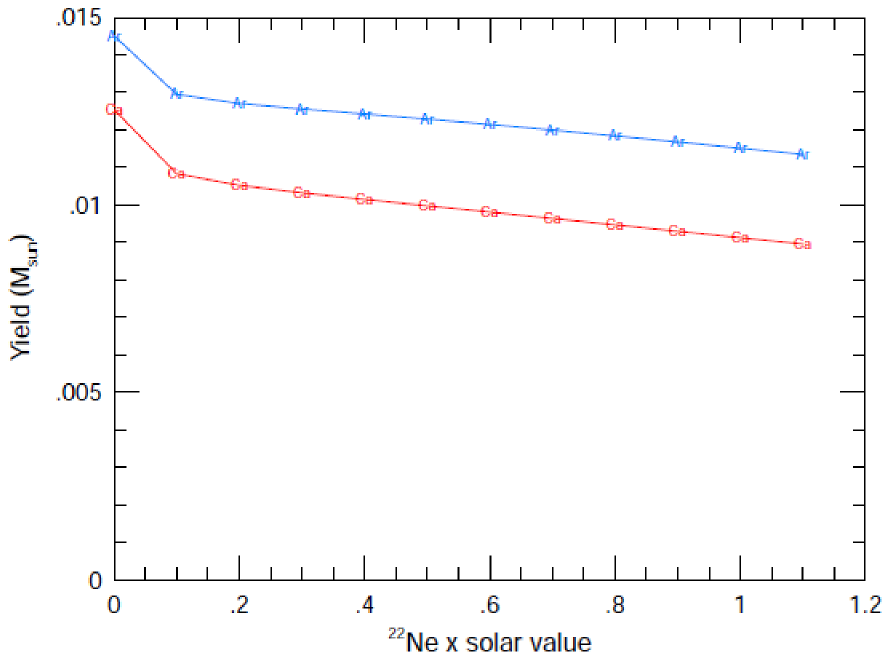
[chamulak et al.]

Additional models?

W7 model shows the same trend.

GCD and sub-Chandra models also show the trend





What next?

- Radiation transport calculations to generate synthetic spectra and light curves.
  - Comparison with observations
- Sensitivity study
- Better understanding of flames at low density.

Conclusions & Collaborators

.SNe Ia seam to know something about the type of galaxy they are in.

Initial composition affects the nucleosynthesis taking place in SNe Ia.

While composition may contribute to some of the observed scatter in luminosities it probably is not the only thing.

There is a systematic trend in the nucleosynthesis of Si group elements with metallicity.

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